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Aircraft Structures Report 433

ON THE MEAN STRESS DEPENDENCE OF THE THERMOELASTIC PARAMETER FOR THREE HIGH STRENGTH ALLOYS (U)

by

S.A. Dunn, A.K. Wong and J.G. Sparrow

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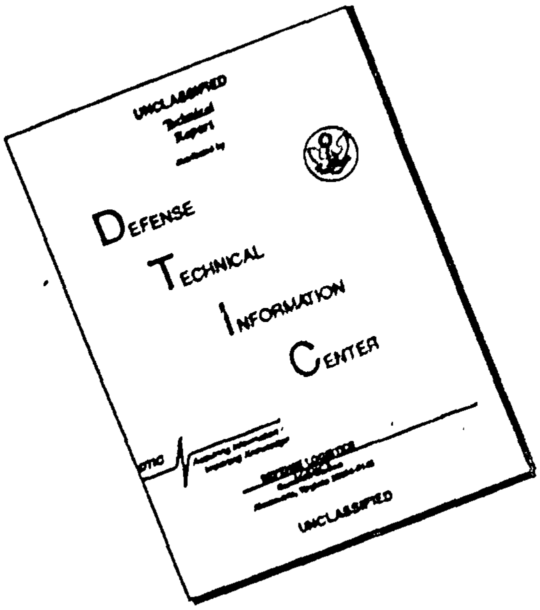

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AIRCRAFT STRUCTURES REPORT 433

ON THE MEAN STRESS DEPENDENCE OF THE THERMOELASTIC PARAMETER FOR THREE HIGH STRENGTH ALLOYS (U)

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S.A. DUNN, A.K. WONG and J.G. SPARROW

SUMMARY

Experimental verification for the theoretical basis of the mean stress dependence of the thermoelastic parameter is presented here for 4340 steel and collated with previous results for 2024 aluminium and 6Al-4V titanium alloys. Various experimental techniques are described and their relationship with the theory is discussed in detail. Finally, the means by which the thermoelastic effect may be used to determine residual stresses in practice is discussed.

DSTO ARL
MELBOURNE

POSTAL ADDRESS: Director, Aeronautical Research Laboratory,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia

CONTENTS

1. INTRODUCTION

A device for the measurement of stress using the thermoelastic effect has become available only within the past six years. This device is a SPATE 8000 (Appendix 1). The thermoelastic effect was first quantified by Lord Kelvin in 1853 [1] and is embodied in Kelvin's Law, which states that the normalised rate of change in temperature varies linearly with the rate of change in the sum of principal stresses. The constant of proportionality, K, between the change in temperature and the change in stress, is known as the thermoelastic parameter. Recent work at this Laboratory has shown that the thermoelastic parameter varies with mean stress. This was first shown by Machin *et al* [2] by a series of experiments in which a constant cyclic stress amplitude was applied to a specimen whilst varying the mean stress. A SPATE 8000 was used to show that the change in temperature arising due to the cyclic change in stress was different for different mean stresses. The theoretical basis for this mean stress dependence was subsequently developed by Wong *et al* [3]. In [3], it was also shown that for an applied sinusoidal cyclic stress, there is a temperature response both at the frequency of loading and at twice this frequency. Wong *et al* [4] showed experimentally how this second harmonic in the temperature response may be used to quantify the mean stress dependence of the thermoelastic parameter. Another means of quantifying the mean stress dependence which involved investigating the quadratic relationship between the temperature response with applied stress was also presented in [4].

The previous references cited results for 2024 aluminium and 6Al 4V titanium alloys. This paper collates these results and presents further results for 4340 steel.

2. THEORY

In [3], it was shown that, for a homogenous Hookean material subjected to uniaxial stress under adiabatic conditions, the thermoelastic equation may be written as

$$\rho_0 C_\epsilon \frac{\dot{T}}{T} = -\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s\right)\dot{s} \tag{2.1}$$

where,

T is the absolute temperature (K)

s is the sum of principal stresses (N/m^2)

ρ_o is the density (kg/m^3)

C_ϵ is the specific heat under constant strain (Nm/K)

α is the coefficient of linear thermal expansion (K^{-1}), and

E is the Young's modulus (N/m^2).

By rearranging, eqn(2.1) may be rewritten as

$$\frac{\dot{T}}{T} = -K\dot{s}, \tag{2.2}$$

where K is the thermoelastic parameter. By comparison of equations (2.1) and (2.2) it can be seen that K is stress dependent. The aim of the following experiments is to quantify this stress dependence and to compare the experimentally obtained values with those predicted by theory.

3. EXPERIMENTS

The changes in temperature with applied stress measured here, and reported in [2] and [4], were made using a SPATE 8000. The infra red detector of SPATE responds linearly to changes in irradiation flux, $d\phi$, which, from the Stefan-Boltzman law, is related to the small change in surface temperature by the expression

$$d\phi = 4\epsilon BT_o^3 dT, \tag{3.1}$$

in which ϵ is the surface emissivity and B is the Stefan Boltzman constant. The SPATE signal is processed using a Brookdeal Model 5206 Correlator which, in normal use, analyses only the component of the detector response which is at the frequency of loading. For a cyclic stress of amplitude, Δs, about a mean stress, s_m, at temperature T_o, it can be shown, by integrating eqn(2.1) and substituting into eqn(3.1), that the SPATE output, S, is

$$S = -4\epsilon RBT_o^4\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)(\rho_o C_\epsilon)^{-1}\Delta s, \tag{3.2}$$

where R is the detector response factor. Equation (3.2) may be rewritten as

$$S = -4\epsilon RBT_o^4 K\Delta s, \tag{3.3}$$

in which the effective thermoelastic parameter, K, is given by,

$$K = \left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)(\rho_o C_\epsilon)^{-1}. \tag{3.4}$$

Equation (3.4) shows that the thermoelastic parameter has a linear dependence on the mean stress, s_m. A normalised measure of this mean stress dependence is, therefore,

$$\frac{1}{K_o}\frac{\partial K}{\partial s_m} = -\frac{1}{\alpha E^2}\frac{\partial E}{\partial T}. \tag{3.5}$$

where K_o is the thermoelastic parameter for zero mean stress ($K_o = \alpha/(\rho_o C_\epsilon)$).

All of the specimens discussed in the following sections, including the 2024 aluminium and 6Al 4V titanium alloy specimens used in [2] and [4], were screw ended with working sections of circular cross-section. The cross-sectional areas were $0.822 \times 10^{-4}\text{m}^2$ for the aluminium alloy specimen, $1.003 \times 10^{-4}\text{m}^2$ for the titanium alloy specimen and $0.040 \times 10^{-4}\text{m}^2$ for the steel specimen. All of these alloys are relatively high strength alloys of their respective base metals with the yield stress of 2024 aluminium being 325MPa, that for 6Al 4V titanium being 960MPa and 4340 steel being 1300MPa.

3.1 Direct Measurement of the Mean Stress Effect

Machin *et al* [2] described how the mean stress effect may be measured *directly* by observing the change in SPATE response for different mean stresses with a constant cyclic stress. Briefly, the method involved focussing the infra-red detector at a single point on a specimen. The specimen was subjected to a cyclic load ,the amplitude of which remained unaltered for the test duration. The mean load was then set to a value and, after 20-30 seconds, a reading of the voltage output from the detector was taken from the the digital display of the Brookdeal correlator. The time delay between the setting of the load and taking a reading was to allow the detector response to stabilise. This method was used in [2] to determine the mean stress dependence of K for 6Al-4V titanium and 2024 aluminium alloys.

Another means of directly measuring the mean stress effect, used here for 4340 steel, is to collect data from the Brookdeal correlator and the testing machine load transducer via a data acquisition system (the data acquisition system used here

was a Hewlett Packard 7090A Measurement Plotting System). This is considerably faster than the previous method and allows the gathering of much more data, thereby giving a better statistical analysis. To do this, the channel 1 output was taken from the correlator (this is a d.c. signal linearly proportional to the reading given on the correlator's digital display) and input to one channel of an analogue to digital converter. A signal from the load transducer was passed through a low-pass filter, such that only the d.c. component of the signal was allowed through, and was captured on another channel of the a-d converter. The data acquisition unit was then set to collect 1000 points of data per channel for 60 seconds, during which time the mean load was constantly varied. The two sets of data may now be analysed using a linear regression analysis to calculate the change in SPATE response with mean load. It is important to note that the measured quantities here are voltages. The gradient obtained from the regression analysis is $\partial V'/\partial V_m$ where V' is the SPATE output and V_m is is the mean load voltage output. The intercept, V_o, is the SPATE output for zero mean load. In relating these voltages to the thermoelastic parameter, we have [5],

$$K = \frac{DRV_s}{Tp_t e \Delta s}, \tag{3.6}$$

where,

- D is the system sensitivity (14.5 K/V)
- R is the temperature correction factor (R=1.0 for $T_o = 20°C$)
- T is the absolute temperature (K)
- p_t is the pellicle transmission factor (0.86)
- e is the surface emissivity (0.92)
- V_s is the detector response (V)
- Δs is the amplitude of cyclic stress (Pa).

Also,

$$V_s = \frac{V'\lambda}{10} \tag{3.7}$$

where,

- V' is the correlator's channel 1 output, and
- λ is the correlator sensitivity.

The applied load, and, therefore stress, s, is measured by a load cell, the output of which is also a voltage, V_L.

$$V_L = \frac{P}{\eta} \tag{3.8}$$

in which,

P is the applied load (N)

η is the calibration factor of the load cell (5000N/V). The applied load can be expressed as

$$P = sA \tag{3.9}$$

where,

A is the cross sectional area (m^2)

and the mean stress, s_m, is therefore given by

$$s_m = \frac{\eta}{A} V_m \tag{3.10}$$

where,

V_m is the mean level of V_L

and the amplitude of cyclic stress, Δs, is,

$$\Delta s = \frac{\eta}{A} \Delta V \tag{3.11}$$

where,

ΔV is the amplitude of the cyclic component of V_L

Bringing together equations (3.4),(3.6),(3.7),(3.10) and (3.11) we have,

$$\frac{DRV'\lambda A}{T\epsilon\eta\Delta V} = \frac{\alpha}{\rho_o C_\epsilon} - \frac{1}{\rho_o C_\epsilon}\frac{1}{E^2}\frac{\partial E}{\partial T}\frac{\eta}{A}V_m \tag{3.12}$$

The output from the correlator is

$$V' = \frac{T\epsilon\eta\Delta V}{DR\lambda A}\left(\frac{\alpha}{\rho_o C_\epsilon} - \frac{1}{\rho_o C_\epsilon}\frac{1}{E^2}\frac{\partial E}{\partial T}\frac{\eta}{A}V_m\right) \tag{3.13}$$

For zero mean load,

$$V'_o = \frac{T\epsilon\eta\Delta V}{DR\lambda A}\left(\frac{\alpha}{\rho_o C_\epsilon}\right) \tag{3.14}$$

The gradient of the change in correlator output, V', with mean load level voltage, V_m, is

$$\frac{\partial V'}{\partial V_m} = -\frac{T\epsilon\Delta V}{DR\lambda}\frac{1}{\rho_o C_\epsilon}\frac{1}{E^2}\frac{\partial E}{\partial T}\left(\frac{\eta}{A}\right)^2 \tag{3.15}$$

Therefore, a normalised measure of $\partial V'/\partial V_m$ is

$$\frac{1}{V'_o}\frac{\partial V'}{\partial V_m} = -\frac{1}{\alpha}\frac{1}{E^2}\frac{\partial E}{\partial T}\frac{\eta}{A} \tag{3.16}$$

Comparing equations (3.5) and (3.16), it can be seen that a normalised measure of the mean stress dependence of the thermoelastic parameter, $1/K_o \partial K/\partial s_m$, is

$$\frac{1}{K_o}\frac{\partial K}{\partial s_m} = \frac{A}{\eta}\frac{1}{V'_o}\frac{\partial V'}{\partial V_m} \tag{3.17}$$

Therefore, the values required to be experimentally determined are the results from the linear regression analysis, V'_o and $\partial V'/\partial V_m$, and A/η. The value A/η can be described as the load cell voltage per unit of applied stress.

3.2 Analysis of Harmonics

It was shown in [4] that under an applied stress of the form

$$s = s_m + \Delta s \sin \omega t, \tag{3.18}$$

where s_m and Δs are the applied mean stress and the amplitude of cyclic stress respectively, and ω is the frequency of loading, eqn(2.1) may be integrated to give

$$\rho_o C_\epsilon \frac{\Delta T}{T_o} = -\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)\Delta s \sin \omega t - \frac{1}{4E^2}\frac{\partial E}{\partial T}(\Delta s)^2 \cos 2\omega t. \tag{3.19}$$

Equation (3.19) shows that there are two frequency components in the temperature response arising from a sinusoidal change in stress. The first component is at the fundamental loading frequency, ω, and is dependent on both the cyclic stress

amplitude and the mean stress. The second component, at the second harmonic, 2ω, is dependent only on the cyclic amplitude of stress. The temperature response, ΔT, to change in stress may be described as

$$\Delta T = a\Delta s \sin \omega t + b\Delta s^2 \cos 2\omega t \tag{3.20}$$

where the ratio, b/a, for $s_m = 0$, is

$$\frac{b}{a} = \frac{1}{4\alpha E^2}\frac{\partial E}{\partial T} \tag{3.21}$$

Substituting eqn(3.11) into eqn(3.20) gives

$$\Delta T = a\frac{\eta}{A}\Delta V \sin \omega t + b(\frac{\eta}{A}\Delta V)^2 \cos 2\omega t \tag{3.22}$$

and the detector response is linearly proportional to ΔT. The ratio of b' to a', where b' is the amplitude of the detector response at 2ω and a' is that at ω, is

$$\frac{b'}{a'} = \left|\frac{b}{a}\frac{\eta}{A}\Delta V\right|. \tag{3.23}$$

Substituting eqn(3.21) into eqn(3.23) gives the ratio of the measured amplitudes, b'/a', as being,

$$\frac{b'}{a'} = \left|\frac{\eta}{4A}\frac{1}{\alpha E^2}\frac{\partial E}{\partial T}\Delta V\right|. \tag{3.24}$$

Comparing eqn(3.24) with eqn(3.5) shows

$$\left|\frac{1}{K_\circ}\frac{\partial K}{\partial s_m}\right| = \frac{4A}{\eta}\frac{b'}{a'}\frac{1}{\Delta V} \tag{3.25}$$

A technique based on eqn(3.25) was used to quantify $1/K_\circ \partial K/\partial s_m$ in [4] for 6Al-4V titanium alloy. In [4], a specimen was cycled about a zero mean load for various cyclic amplitudes. The 'raw' detector response was analysed using an FFT analyser ('raw' detector output refers to the uncorrelated detector response). The ω and 2ω components of the detector response, a' and b' in eqn(3.25) respectively, were then determined

3.3 General Response Law

Another means of indirectly quantifying the mean stress effect is via the general response law, as described in [4]. It was shown that, by measuring the quadratic nature of the thermal response to an applied stress, a value for the mean stress dependence of the thermoelastic parameter may be derived. The general response law is

$$\rho_o C_\epsilon \frac{T - T_o}{T_o} = -(s - s_o)\left(\alpha - \frac{1}{2E^2}\frac{\partial E}{\partial T}(s + s_o)\right) \tag{3.26}$$

where s_o is the stress at $T = T_o$. By expansion of eqn(3.26), it can be seen that the change in temperature varies quadratically with stress as

$$\Delta T = a_1 s + a_2 s^2 + k \tag{3.27}$$

and that the ratio a_2/a_1 is

$$\frac{a_2}{a_1} = -\frac{1}{2\alpha E^2}\frac{\partial E}{\partial T}. \tag{3.28}$$

From eqn(3.11), the actual measured values can be described as

$$\Delta T = a_1 \frac{\eta}{A}\Delta V + a_2(\frac{\eta}{A})^2 \Delta V^2 \tag{3.29}$$

such that the ratio, a_2'/a_1', of the coefficient of the second order term to that of the linear component as determined by a regression analysis of the SPATE signal against the load cell response is,

$$\frac{a_2'}{a_1'} = \frac{a_2}{a_1}\frac{\eta}{A}, \tag{3.30}$$

the substitution of eqn(3.28) into eqn(3.30) gives

$$\frac{a_2'}{a_1'} = -\frac{\eta}{2A}\frac{1}{\alpha E^2}\frac{\partial E}{\partial T}. \tag{3.31}$$

Comparing eqn(3.31) with eqn(3.5) shows

$$\frac{1}{K_o}\frac{\partial K}{\partial s_m} = \frac{2A}{\eta}\frac{a_2'}{a_1'} \tag{3.32}$$

So, by investigating the quadratic nature of the detector response to applied stress, the mean stress dependence of the thermoelastic parameter may be quantified in a similar way to that used in the analysis of the harmonic content of the temperature response to a sinusoidal change in stress. The advantage of this method, however, is that by making use of the general response law, a purely sinusoidal load input is not required.

This method was used to measure $1/K_o \partial K/\partial s_m$ for 4340 steel and for 6Al 4V titanium alloy in [4]. To do this, the 'raw' detector output was firstly filtered through a 40Hz low pass filter to remove a large component of the 'white' noise and 50Hz mains pick-up which was evident on the detector signal. A dynamic loading was then applied to the specimen which, whilst not necessarily sinusoidal, must still give a sufficient rate of change of stress for adiabatic conditions to be maintained. The filtered detector response and the load cell signal were then collected for 2 seconds (1000 samples per channel) on a Hewlett Packard 7090A Measurement Plotting System. The data were then analysed on a computer. The computer program first had to realign the data sets to account for the time shift introduced by the filter (this was minimised by passing the load cell signal through a similar filter). A regression analysis was then performed to fit a curve of the form of eqn(3.29). The results of the regression analysis were used to determine a normalised measure of the mean stress dependence as shown in eqn(3.32).

For the 4340 steel specimen, it was found that repeatable results for the ratio a_2'/a_1', as described in eqn(3.32) could be obtained only for cyclic stress amplitudes of 600MPa or greater. As a consequence, measurements were taken for cyclic stress amplitudes ranging from 620MPa to 870MPa.

4 RESULTS

Three materials considered here are Ti-6Al-4V, Al-2024 and 4340 Steel. The relevant material properties for these materials are given in Table (4.1).

Material	α (K^{-1})	E (MPa)	$\partial E/\partial T$ (MPa/K)
Ti-6Al-4V	9.0×10^{-6}	1.11×10^{5}	-48.0
Al-2024	2.3×10^{-5}	7.20×10^{4}	-36.0
4340 Steel	11.2×10^{-6}	2.10×10^{5}	-56.7

Table (4.1) Material properties for the three alloys tested.

The results for the mean stress dependence of these materials and the means by which they were achieved are given in Table (4.2).

Material	$\partial K/\partial s_m K_o^{-1}$ (MPa^{-1})				
	Theory Eqn.(3.5)	1.†	2.	3.	4.
Ti-6Al-4V	4.33×10^{-4}	4.29×10^{-4} [2]	—	4.52×10^{-4} [4]	4.28×10^{-4} [4]
Al-2024	3.02×10^{-4}	3.19×10^{-4} [2]	—	—	—
4340 Steel	1.15×10^{-4}	—	1.25×10^{-4}	—	1.10×10^{-4}

†1. Recording the correlator output for discrete mean stresses

2. Changing the mean stress with correlator output recorded using a data acquisition system

3. Measurement of detector response at ω and 2ω

4. Analysis of quadratic nature of detector response

Table (4.2) Comparison of experimental and theoretical results for the mean stress dependence of the thermoelastic parameter.

5 DISCUSSION

As shown in Table (4.2), each method of quantifying the mean stress effect described here produced values in close agreement with those predicted by theory.

There are two main purposes to this work. Firstly, to show that calibrations of SPATE, taking into account the mean stress effect, can be successfully performed. Secondly, to pursue the possibilities of using the mean stress dependence to determine residual stresses. With the successful quantification of the mean stress dependence of the thermoelastic parameter, the first aim has been successfully completed. The second aim presents a few more problems. To detect residual stresses, it would be ideal to be able to measure the thermoelastic parameter and, from there, using the material constants, infer the residual stresses. The problem with this is that to be able to determine the thermoelastic parameter, the applied stress must be known. In practical applications, it must be assumed that the applied stresses will be just as much of an unknown as any residual stresses which may exist. The methods used here (that is, quantifying $1/K_o \partial K/\partial s_m$) are not sufficient to show residual stresses. This is because, as can be seen in equations (3.23) and (3.30), the applied stress per unit of load cell voltage must be known. Where it is possible to measure residual stress, however, is in taking measurements of the two components of equation (3.19) such that, with these measurements, this equation may be broken up into two parts and treated as two separtate equations with Δs and s_m being the two unknowns. This can be shown by rewriting equation (3.19) to make ΔT the subject

$$\Delta T = \frac{-T_o}{\rho_o C_\epsilon}\left(\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)\Delta s \sin\omega t + \frac{1}{4E^2}\frac{\partial E}{\partial T}(\Delta s)^2 \cos 2\omega t\right). \tag{5.1}$$

Letting a' and b' be the amplitudes of the detector response at ω and 2ω, it can be seen that

$$a' = \left|\frac{1}{k}\frac{T_o}{\rho_o C_\epsilon}\left(\alpha - \frac{1}{E^2}\frac{\partial E}{\partial T}s_m\right)\Delta s\right| \tag{5.2}$$

and,

$$b' = \left|\frac{1}{k}\frac{T_o}{\rho_o C_\epsilon}\frac{1}{4E^2}\frac{\partial E}{\partial T}(\Delta s)^2\right| \tag{5.3}$$

where k is a detector response factor.

Equation (5.3) may be rearranged to give

$$\Delta s = \sqrt{\left|\frac{kb'\rho_o C_\epsilon}{T_o} \frac{4E^2}{\partial E/\partial T}\right|} \tag{5.4}$$

and, since for most practical applications with metals $(\alpha - 1/E^2 \partial E/\partial T s_m) > 0$, equation (5.2) gives

$$s_m = \left(\frac{-ka'\rho C_\epsilon}{T_o \Delta s} + \alpha\right) \frac{E^2}{\partial E/\partial T} \tag{5.5}$$

Substituting (5.4) into (5.5) will give the mean stress at any point. This is slightly more complex than the analysis presented here because two more material properties, the density, ρ_o, and the specific heat at constant strain, C_ϵ, are required. If these material properties are not available then the results may still be calibrated by having a strain gauge in a region of uniform cyclic stress amplitude such that equation (5.4) may be equated with the strain gauge data. A quadratic analysis via the general response law may be treated in a similar manner. Such signal processing will offer the possibility of producing area scans showing both cyclic and mean stresses.

Given the signal processing equipment and techniques used to date, it has been found that prohibitively high cyclic stresses are required to give consistent values for b and a_2 in equations (3.23) and (3.30) respectively. More work is required to develop better signal processing techniques such that these numbers may be successfully extracted for much smaller cyclic stresses. With this, area scans showing residual stresses will become a practical proposition.

6 CONCLUSION

The mean stress dependence of the thermoelastic parameter was experimentally determined and collated, together with the results from [1] and [3], in this report for three alloys using four different techniques. In each case, good correlation between the experimental results and the theoretically predicted values were found. This suggests that the theory can be confidently used to predict the mean stress dependence for other alloys given the required material properties.

Further work is required to show that the mean stress dependence of the thermoelastic parameter may be used to measure residual stresses in a practical situation.

ACKNOWLEDGMENTS

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APPENDIX 1

SPATE 8000

SPATE is an acronym for Stress Pattern Analysis by measurement of Thermal Emission. The SPATE 8000 is manufactured by Ometron Ltd. in the U.K. and is a device for non-contact stress measurement by determining the change in temperature of a body as it undergoes a change in stress. This change in temperature is as described by the thermoelastic effect.

Once a body undergoes a change in stress, resulting in a change in temperature, the laws of heat transfer dictate that the body must return to the ambient temperature once the source of heat generation is removed. To be able to measure the maximum temperature change due to the changing stress, the body must undergo a constantly changing or cyclic stress at a sufficient rate for adiabatic conditions to be maintained. This means that the rate of change of stress must be sufficient for there to be little or no heat transfer from one point to another during the period of the cycle.

The changes in temperature generated by theses stress changes is measured using a liquid nitrogen cooled infra-red detector. A cyclic reference signal may be extracted from a load transducer or an accelerometer. This reference signal along with the signal from the infra-red detector are then analysed using a Brookdeal correlator. The correlator serves to extract the component of the infra-red detector signal that is at the frequency of the reference signal, or the frequency of loading. Such correlating has two main advantages. Firstly, the recorded SPATE signal is relatively insensitive to external thermal and electrical influences at anything but the frequency of loading. Secondly, SPATE has a very high sensitivity at the frequency of loading giving it a temperature resolution of 0.001K. This temperature resolution corresponds to changes in stress of 1MPa in steels and titianium alloys and 0.4MPa in aluminium alloys.

The optics of SPATE give it an optimum spatial resolution of 0.5 mm diameter with the detector 250mm from the specimen. This spatial resolution decreases linearly with the distance between the detector and the specimen such that at 1m the spot size is of 1.25mm diameter.

To increase the thermal emissivity of a specimen, ϵ in equation (3.6), it is painted with a heat radiating paint with an ϵ of 0.92 (the emmissivity of bare metals is commonly around 0.2).

In the normal use of SPATE, scan limits are specified on the specimen and the desired resolution is input (the resolution defines the number of scan points along the longest edge of the specimen). An integration time per point is entered and a raster scan performed, the results of which are displayed in real time on a colour monitor. The scan data are held in temporary storage in solid state computer memory and may be transferred to floppy disc for permanent storage. Scan data may also be transferred to a host computer via an RS232 C link.

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S.A. DUNN, A.K. WONG and J.G. SPARROW

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AERONAUTICAL RESEARCH LABORATORY
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Experimental verification for the theoretical basis of the mean stress dependence of the thermoelastic parameter is presented here for 4340 steel and collated with previous results for 2024 aluminium and 6Al-4V titanium alloys. Various experimental techniques are described and their relationship with the theory is discussed in detail. Finally, the means by which the thermoelastic effect may be used to determine residual stresses in practice is discussed.

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